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Research Article

Experimental Validation of the Well-Density Profile for Immiscible Gas Enhanced Oil Recovery Projects

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ABSTRACT

The well-density profile of Immiscible Gas Enhanced Oil Recovery (IGEOR) processes for CH_4, N_2, Air, and CO_2 has been investigated through rigorously data mining and experimental methods. Well-density has significant engineering and economic implications for EOR project evaluation because wells determine the amount of oil produced from reservoirs, and they are the most expensive subsurface infrastructure of an oilfield. Some authors have investigated EOR technology characterisation in the literature, nevertheless, there are few to no resources that has simultaneously evaluated the well-density competitiveness of the four gases used in IGEOR. The outcome of this study has objectively contributed to reservoir knowledge and practice by indicating that Gas EOR processes can be characterised by well-density. It has been demonstrated that the CH_4 EOR process offers the lowest well-density (0.96 wells.cm^{-2}), while the CO_2 offers the highest well density (1.5 wells.cm^{-2}). This implies that selecting to inject CH_4 in reservoirs rather than CO_2 can reduce well cost and engineering complexity by nearly half. The structural rhythm that optimises well density in a heterogenous and layered reservoir was found to be akin to a positive porosity gradient, that is, injection direction is from lower porosity region to higher porosity region. The low coefficient of variation of CO_2 in the data mining and experiments suggest that the recovery performance of the gas would be most sensitive to well density deviations. The quality of the coupled analyses indicates that the experimental results sufficiently validate the data mining results. Consequently, in the order of competitiveness, the EOR gases rank as CH_4>Air>N_2>CO_2. This research finds direct utility in EOR screening of reservoirs and the selection of gases appropriate for the effective displacement of trapped oil.

Keywords: EOR cost; Reservoir characterization; Injectants; Gas EOR; Well-density; Well cost

INTRODUCTION

The well-density (W_{Den}) as shown in Equation (1), is used to estimate the sum of injection (W_1) and production (W_P) wells required to optimally drain a unit area (W_P) of a reservoir undergoing a particular EOR technology [1-2].

$$W_{Den}=(W_P+W_1)/A \quad (1)$$

Shepherd [2-3] stated that the optimal achievable drainage for a reservoir depends on the number of production and injection wells. Therefore, suggesting that the coupling of EOR processes and Well-density to recover trapped oil in reservoirs has economic and engineering implications. The theoretical expectation is that some EOR processes and reservoirs may show a profile consistent with high well-density than others. This leads to the following questions:

How important is such knowledge to reservoir engineering? First, it is only a properly planned and executed well-density model that can effectively drain trapped oil, produce the maximum recovery efficiency, and minimise project complexity, such as well conversion, infill well drilling, maintenance, and shutdown.

How important is this knowledge to reservoir economics? Wells are the single most expensive subsurface activity in an oil field [2]. It takes between 15 to 27 million dollars and 10 to 40 days to

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drill a well [4-8]. Consequently, the ultimate economic aim is to the minimised cost and maximised revenue. The economist, therefore, needs to guarantee top management that these costs can be recovered from the incremental oil resulting from the drilled wells. However, where the correct connecting information cost and recovery performance is not available or applied in decision making, this could result in a catastrophic loss of revenue.

IGEOR is a subset of EOR technologies. It involves injecting gases to displace oil droplets trapped by forces such as capillary forces. The uniqueness of IGEOR is that gas-oil miscibility is not required for the displacement. The displacement resembles a piston-like displacement. At the moment, existing EOR screening models presented by investigators such as [9-16] do not include well density as a criterion for selecting gases used in IGEOR. Nevertheless, where there is significant well density segregation amongst injected fluids, such outcome would help persuade the industry to consider the inclusion of well density in the early stages of EOR screening models, to be at par with other screening criteria such as permeability, viscosity, and API gravity.

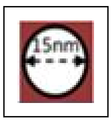
Well density and its impact on various EOR performances is an area that has not been investigated thoroughly. There was hardly any direct or recent journal article found in this subject matter with respect to EOR methods. Many studies on well density focus on primary and secondary oil recovery. Holm [16] compared infill wells and EOR implementation as two competing oil recovery strategies that could also be combined for synergetic oil recovery. The author, however, submitted that well spacing is critical to chemical EOR than to gas EOR. The author further reported that short-circuiting of displacing fluids, such as CO_2, could be reduced by maintaining the often applied well spacing of 40 acres in reservoirs with high permeability. Using numerical data analysis in the US oilfields, [17-18] agreed that increased well density improves the ultimate recovery factor. However, the two authors disagreed on the mechanism, conditions and extent of such improvement. Kern [19] did a data analysis of 48 reserves in the Permian Basin and concluded that in water flooded reservoirs with lower permeability (<1.2mD), there is a significant correlation between well spacing and recovery efficiency. However, at higher permeability (>1.2dm), no correlation was observed. On the contrary, Suman [20] rejected the previous authors' claims of the relationship between well spacing and recovery efficiency, insisting that the most significant recovery is achieved from relatively sparse well density. It would be observed that not only are these authored works old, but they are also not much agreement in their respective positions. A more recent study by [3], suggests that well density improves oil recovery efficiency; however, beyond 3 wells.km^{-2}, the oil recovery efficiency graph plateau or flattens out, but their study did not include an EOR situation that involves a fluid injection process.

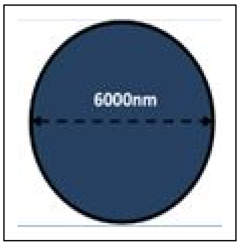
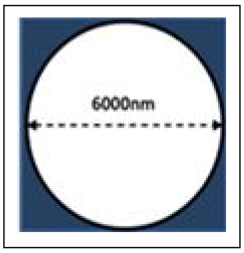
Although many studies have characterised EOR on technology and petrophysical properties basis [9-15, 21], and few have investigated well density [3, 16-20], none has simultaneously compared the well-density competitiveness of gases such as CH4, N2, Air, and CO_2 in IGEOR processes. Therefore, this study aims to characterise and evaluate the well-density models of the respective gas EOR processes with a focus for IGEOR. The optimisation objective is to minimise well-density and to identify the structural settings that enables optimisation in a heterogenous or layered system. The comparative objective is to identify the IGEOR process that offers the least Well-density.

MATERIALS AND METHODS

A global database consisting of 350 EOR projects was generated and analysed using Equation (1). Data mining techniques were applied to characterise gas EOR processes using reservoir area and well data reported in EOR field projects across the world. The outcomes from the data mining were used to design gas experiments. The research applied materials such as gases (CH_4, N_2, Air, and CO_2) and five analogue core samples possessing varying structural parameters that are obtainable in reservoir settings Table 1. The experiments operating conditions were designed to be similar or extrapolatable to reservoir conditions. Thus, the pressure range is 20 to 300KPa, and there were eight isotherms within the range of 293 to 673K. The experimental set-up and equipment used are shown in Figure 2.

Table 1: Structural parameters of core samples.

Porous Sample	Structural Parameters			
	Geometry		Porosity	Aspect Ratio
	Pore Size	Radial Thickness		
0.1		0.14cm	φ =13%	10E+04
2		0.25cm	φ =3%	2E+05

3		0.16cm	φ =20%	8E+03
0.4		0.14cm	φ= 14%	2E+02
0.5		0.24cm	φ= 4%	4E+02

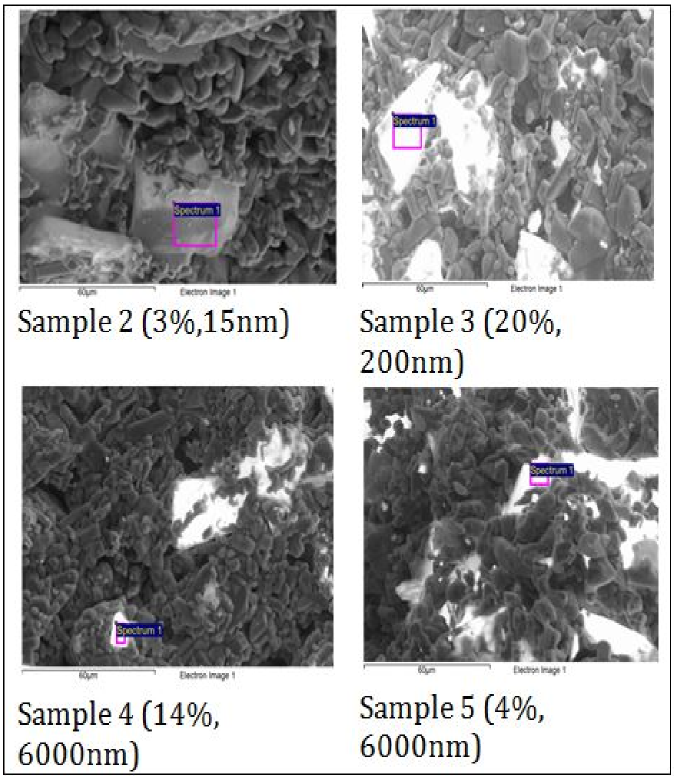


Figure 1: Showing the EDXA characterisation and morphology of four of the samples used in the experiment their porosity and pore size.

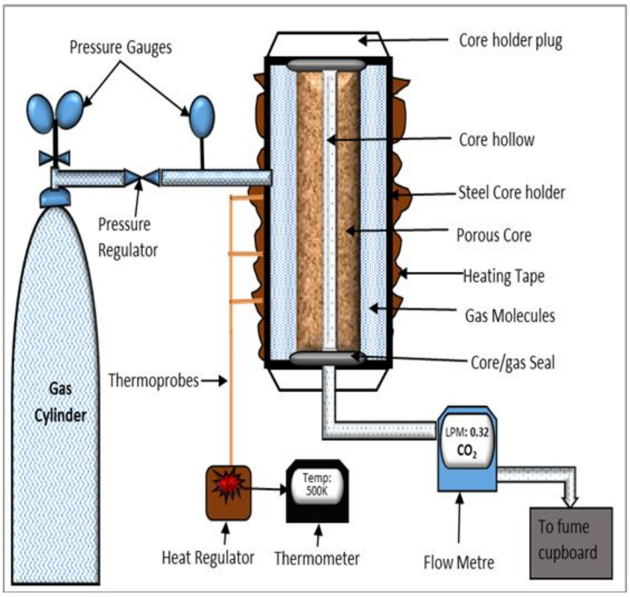


Figure 2: Schematic of the experimental set-up.

Experimental procedure and conditions

- Heated and maintain core system at thermal stability (starting temperature: 293K).
- Injected gas into core system at a set pressure (starting pressure: 0.20 atm)
- Record permeate volume rate, temperature and pressure when steady-state flow is achieved.
- Repeat a-c at intervals of 0.40 atm until the maximum pressure (3.0 atm) is reached.
- Repeat a-d for Temperature 323, 373, 432, 473, and 673K.

For the gas experiments analysis, an empirical-analytical approach was applied to experimental data to estimate and characterise the potential well-density. A single well model was assumed. The gas potential sweep area or areal reach (cm^2) was estimated by normalising the gas volume rate (cm^3) by the equivalent pay zone or height (cm) of the core samples. This facilitated the estimation of the relative potential areal reach of the respective gases at various PVT settings. The outcome of such normalisation is illustrated in Figure 3. The implementations of three gases in a single well injection model has been presented as Gas A, B and C in a hypothetical reservoir of 4cm in diameter (Dr). The gases are injected into the reservoir through the well bore at constant pressure. The permeate volumes (cm^3) of the respective gases are normalised to areal reach (cm^2).

In Figure 3, Gas A has the least areal reach. Therefore, given a reservoir of a set size, selecting to inject Gas A would require 2 times more wells than Gas B and 3 times more well than Gas C. Gas C reaches or sweeps into the farthest extent of the reservoir, covering 72% of the total area of the reservoir at the same injection pressure and time as Gas A and B. This indicates that there may not be need to drill additional infill wells to sweep the reservoir. Consequently, without loss of generalisation, Gas C is the most competitive gas for well economics and engineering in this type of screening scenario.

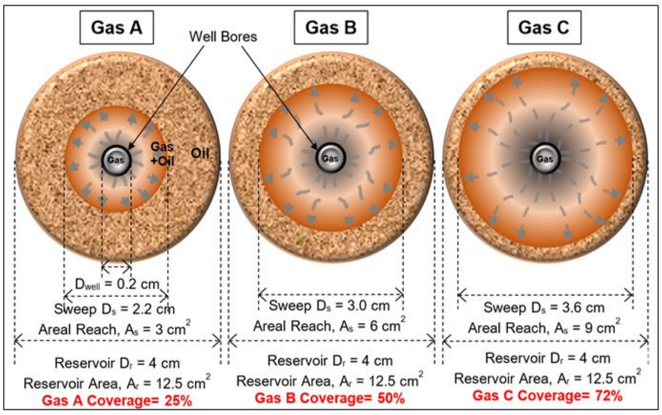


Figure 3: Showing normalized volume models for describing the well requirements for 3 gases as a function of the areal reach of gases.

Some engineering assumptions made to normalize volume to areal reach include: gravity effect on gas permeation is negligible; the energy required for gas lateral permeation of media is available for interstitial permeation.

RESULTS AND DISCUSSIONS

Figures 4a and b show that the experimental well-density significantly couples with well density from the field data found in the database of global EOR projects. From the mean well-density profiles in Figures 4a&b, it is concluded that CH_4 requires the least number of wells for effective reservoir drainage and coverage. In the field data, it is shown in Figure 4a that the CO_2 EOR process (0.07 well.acre^{-2}) would require about three times the number of wells required by the CH_4 EOR process (0.02 well.acre^{-2}) for the same reservoir coverage. The experimental outcome significantly validates the field data model in Figure 4a, where CO2 (1.50 well.cm^{-2}) requires about twice the number of wells required by CH_4 (0.96 well.cm^{-2}). The coefficient of variation (Cv) in both graphs indicates that CO_2 performance is sensitive to well-density variation. Thus, the implication to project engineering and economics is significant. Such that selecting CH_4 EOR process over CO_2 EOR process would invariably save about twice the cost on well drilling, prevent the operational complexity, risk, and downtime required to drill new infill wells, and the shutdown time to maintain existing wells. Consequently, using the experimental data in Figure 4a, the competitive ranking for well-density is CH4>Air>N2>CO2.

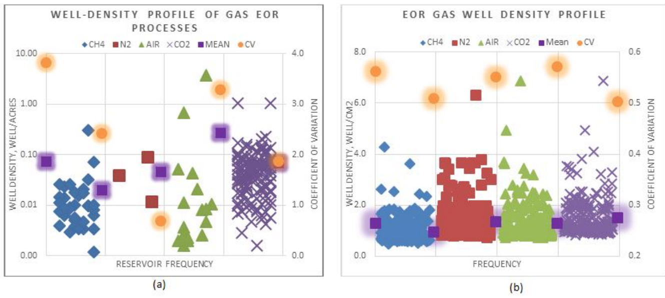


Figure 4: Showing the well-density profile of gas EOR reservoirs in the data mining model (a), and the well-density profile of EOR gases in the experimental model (b).

The data mining investigated well density and porosity relationship. The clusters in Figure 5 indicate that there are different well density profiles along the porosity spectrum (3-65%) investigated. Two significant clusters are identified in Figure 5. For reservoirs with porosity that is below 17%, the well density clustered is limited to the range of 0.002 and 0.2 wells/acre. Between porosity 17% to 38%, the opportunity for well density becomes more extensive. In this porosity spectrum, well density can be as high and as low as 3.00 wells/acre and 0.002 wells/acre, respectively. When the experimental data were analysed for well density and structural parameters such as porosity, it was found that well density optimized at a relatively higher porosity for a homogeneous block of media. Similarly, for a heterogenous block, well density is optimised by a positive porosity gradient. That is, injection well is placed at the region of relatively lower porosity than the production well region. For instance, in Figure 4, CH_4 is found to offer the least well density in data mining and experiments. According to the experimental data and Figure 6, where the 5 media are stacked together to form analogues layered reservoirs, the structural rhythm necessary to achieve the least well density for CH_4 and N_2 suggests that the gases need to be injected into the media with the lowest porosity (Sample 2:3%), and the production or permeate point needs to be located on the side of the stack where the porosity is greatest (Sample 3:20%). For Air and CO_2, the injection is at (Sample 2:3%) and production at (Sample 5:4%). All for gases optimises their well density requirement with a positive porosity gradient. Based on the coupled interpretations of Figure 5 and Figure 6, it can therefore be said that the experimental outcome significantly validates the data mining.

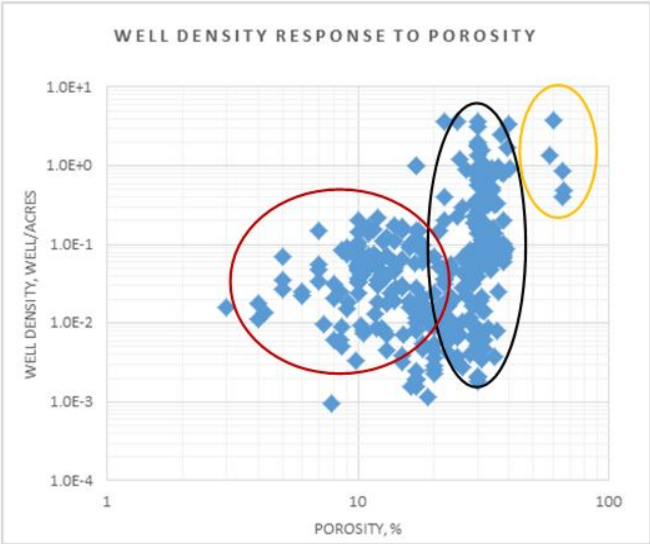


Figure 5: Showing well density against reservoir porosity.

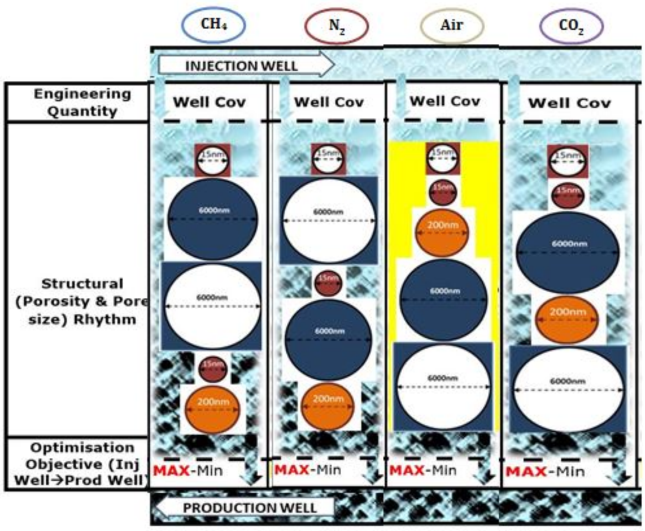


Figure 6: Showing the structural rhythm required to optimise well density for CH_4, N_2, Air, CO_2.

CONCLUSIONS

The well density has been extensively studied through data mining and extensive gas experiments in analogues core samples. The following have been established:

- EOR technologies can be characterised by well density.
- CH require the least well, thus offers the best opportunity for well economics and engineering.
- The ranking of well density competitiveness is CH>Air>N>CO.
- In a multilayered reservoir, well density optimisation is achieved through a positive porosity gradient for all four gases.

Besides oil recovery, the outcome from this study appeals to knowledge and practice in industrial processes such as multi-stage gas separation and reactions that are conducted in porous media. It would facilitate system sizing, membrane structural arrangement, fluid selection, flow optimisation and process effectiveness and efficiency.

It is recommended that well density be included in EOR screening models. It is also recommended that further studies be conducted to investigate the influence of other petrophysical quantities, such as rock types, pore size and oil viscosity, on the well-density profile of IGEOR technologies and processes especially given the nature of the black cluster in Figure 5. It is intuitively expected that other variables are responsible for the extensive well density opportunities observed between porosity 17% to 38%.

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